Protecting Vulnerable Stocks in Multi-species Prawn Fisheries

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Summary

Information from the unusual collapse and rebuilding of individual penaeid stocks within the Western Australian multi-species trawl fisheries assists in developing population models for penaeids and identifies potentially vulnerable prawn stocks. The Exmouth Gulf stock of *Penaeus merguiensis* collapsed in the 1960s and has not recovered. The *P. esculentus* stocks in Shark Bay and Exmouth Gulf suffered recruitment overfishing during the early 1980s, but significant reductions in the fishing effort directed at this species have resulted in increased breeding stock and improved catches; spawning stock–recruitment relationships have been developed for the two *P. esculentus* stocks. No such relationship is clear for the *Penaeus latisulcatus* stock in Shark Bay, but the data suggest that recruitment may be influenced by an environmental effect at the time of recruitment. The ability of a fishery to exert high levels of pre-spawning fishing mortality is a common factor in penaeid fisheries showing recruitment overfishing. Local geography, the position of the fishery within a species range, the presence of other species in a fishery, and the catchability, appear to affect susceptibility to overfishing.

Introduction

The penaeid prawn stocks, which support major tropical and subtropical fisheries throughout the world, have historically been regarded as resilient to recruitment overfishing. Until the early 1980s, there were no documented spawning stock–recruitment relationships (SRRs) for penaeids, and it was believed that the well-documented environmental effects on recruitment were more likely to be the cause of the typically large catch variations from penaeid fisheries (see Garcia 1983 for review). In addition to environmentally driven variations in recruitment obscuring any underlying SRR, data limitations have also contributed to the difficulties in developing reliable recruitment and, particularly, spawning stock indices for the study of SRRs for penaeids (Gulland 1984).

Events in the multi-species penaeid fisheries of Western Australia (WA) during the early 1980s (Penn and Caputi 1985), however, led to renewed scientific debate about the potential impact of fishing on such stocks. Significant reductions in recruitment of tiger prawn stocks in Shark Bay and Exmouth Gulf, and evidence of a discernible SRR (Penn and Caputi 1986), have led to wider acceptance that specific management action to maintain breeding stock levels will be required for some penaeid fisheries.

The purpose of this paper is to review and update the spawning stock and recruitment relationships developed for Western Australian penaeid stocks, and to use these data with information from other recorded cases of penaeid recruitment overfishing to identify stocks in situations in which precautionary management strategies should be adopted.

WESTERN AUSTRALIAN CASE STUDIES

Industrial fishing for penaeid prawns began along the WA coastline during the early 1960s and has been subject to a staged development under a system of limited-entry fishing regulations (Bowen and Hancock 1984). In the early 1960s two major WA fisheries developed along the desert coastline at Shark Bay (26°S) and at Exmouth Gulf (22°S). Smaller discrete fisheries operating off the coast at Onslow, Nickol Bay, and in the Kimberley Bays (Fig. 1) developed in the late 1960s to early 1970s, and a new fishery began off Broome in the mid 1980s. Limited entry management arrangements for each of these fisheries were introduced during 1980–90.

The dominant species in these fisheries, in order of importance, are western king prawns (*P. latisulcatus*), brown tiger prawns (*P. esculentus*), banana prawns (*P. merguiensis*) and endeavour prawns (*Metapenaeus endeavouri*), with total catches in the order of 3500 t having been taken by approximately 90 vessels in 1994 (Anon. 1996). Scientific literature covering the biological and fishery data used to manage the most abundant stocks in the two major fisheries has been summarized by Penn *et al.* (1989).

EXMOUTH GULF FISHERY

The trawl fishery in Exmouth Gulf exploits four species: banana prawns, tiger prawns, western king prawns, and endeavour prawns, with banana prawn and tiger prawn stocks showing a high degree of annual variability (Fig. 2). The fleet was developed incrementally under limited-entry management to a maximum of 23 vessels in 1979–82; however, this number has subsequently been reduced to 19 (1984) and 16 (1990) through industry-funded buy-back arrangements.

Banana prawn stock

Trawling for prawns in Exmouth Gulf began in 1963 with a small fleet that fished in daylight for schools of banana prawns (52 t taken). However, after three years of fishing (1964, 60 t; 1965, 57 t; 1966, 39 t), the catch declined to 22 t in 1967, and by 1968 was an insignificant proportion of the fishery. During 1965 and 1966, the fleet switched to night fishing on the more abundant but less catchable tiger and king prawns. Although no longer targeted by the fleet, small catches of banana prawns (less than 1 t) have continued to be recorded in most subsequent years, indicating that the species is still present but at a consistently low level. On three occasions since 1967, schools of banana prawns have occurred associated with years of high summer rainfall (1976, 17 t; 1990, 5 t; 1995, 9 t); however, on each occasion catches have not been sustained.

Noting that this banana prawn stock is at the southern limit of the species range, the decline in recruitment during the 1960s could be attributed to either a change in an unknown environmental factor that significantly reduced recruit survival, or to an adverse effect of fishing on spawner abundance that led to lower numbers of recruits, or to both factors. The consistent occurrence of fishable quantities (schools) during surveys prior to the development of the fishery and then for three years at low levels of fishing effort (Penn 1984) supports the hypothesis that the effect of fishing pressure has been a significant contributing factor. Similarly, the failure of the stock to rebuild to previous production levels, i.e. above 50 t, despite the occurrence over a 29-year period of the high-rainfall conditions usually favourable to this species, adds further support to the hypothesis that fishing has had a negative impact.

Tiger prawn stock

Night trawling targeting tiger prawns had become the major fishing activity in Exmouth Gulf by 1966. Tiger prawns dominated the catch through to 1980, but with significant year-to-year variations in production (Fig. 2). These annual catch variations from 200 to 1200 t appear to be related to

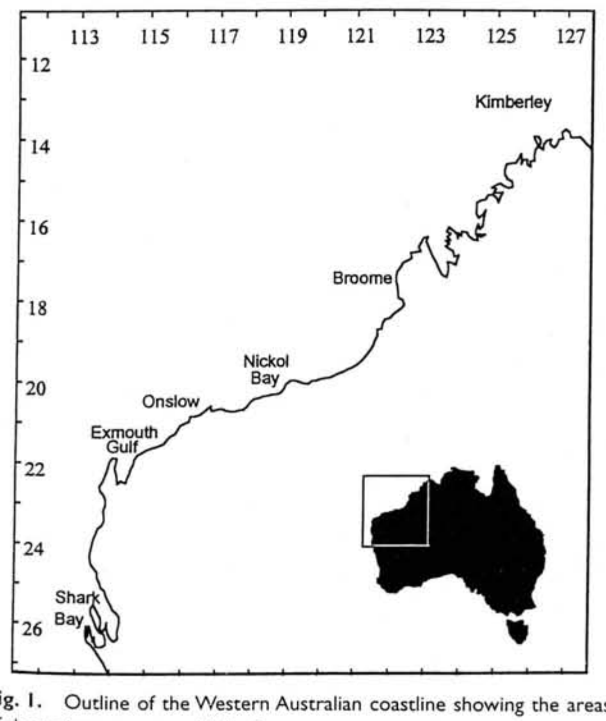

Fig. 1. Outline of the Western Australian coastline showing the areas of the major prawn trawl fisheries.

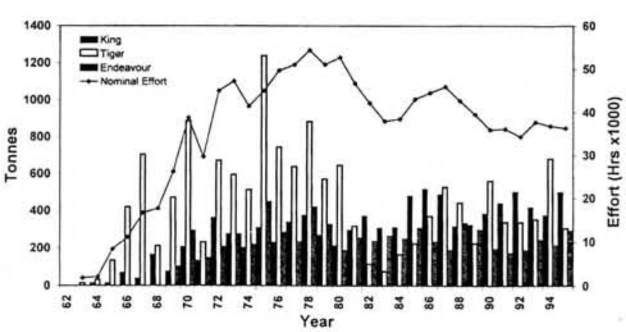

Fig. 2. Catches of the major prawn species taken in the Exmouth Gulf fishery (1963–95) and nominal hours of trawling effort.

cyclone events, although not all cyclones produced good catches (Penn and Caputi 1986). In 1981 and 1982 a significant decline in recruitment, following an escalation in effective fishing effort through vessel replacements and targeted fishing on new recruits, raised concerns that recruitment overfishing had occurred (Penn and Caputi 1985). From the very detailed database for this stock, a strong relationship between spawning stock levels in Spring, and subsequent Autumn recruitment to the fishery and cyclonic activity measured as rainfall was developed (Penn and Caputi 1986). This first recorded SRR for a penaeid stock has been subsequently updated (Penn *et al.* 1995; Caputi *et al.* 1997), and with current years added is shown in Figure 3. Although the basic SRR remains evident ($r = 0.64$), the initial hypothesis to explain the positive and negative impacts of cyclones (Penn and Caputi 1986) has not been supported by recent data. However, exclusion of the two years with extreme cyclone events (1971 and 1975) from the analysis shows a continuing strong relationship between spawning stock and recruitment in typical environmental circumstances ($r = 0.74$). Further assessment of the effects of cyclones on the SRR is constrained by the limited number of cyclone events occurring.

The ability to demonstrate a SRR for this stock exists because of a number of unusual factors. There is relatively little environmental variability in Exmouth Gulf, and those variations that do occur are significant and discrete 'events'. Secondly, there is a detailed database for the fishery which includes the necessary 'contrast' in the spawning-stock levels to allow recruitment to be assessed at both high and low spawning-stock levels. Similarly, the database contains sufficient contrast in levels of effort to allow the impact of fishing on survival to spawning to be assessed. The decline in effort through the early 1980s came about through radical management action including roster fishing by only one-third of the fleet during the recruitment period (March–April) and the closure of the whole tiger prawn area before and during spawning (August to November) in several years.

The impact of fishing as the major cause of the decline in spawning stock was demonstrated by the within-season relationship between an index of recruitment, effective fishing effort, and subsequent spawner index (abundance) (Penn and Caputi 1986). In an update by Penn *et al.* (1995) this relationship continues to show a significant multiple correlation ($r = 0.95$). The effect of fishing is confirmed by the response of the breeding stock, and subsequent recruitment, to management changes that reduce fishing effort and mortality.

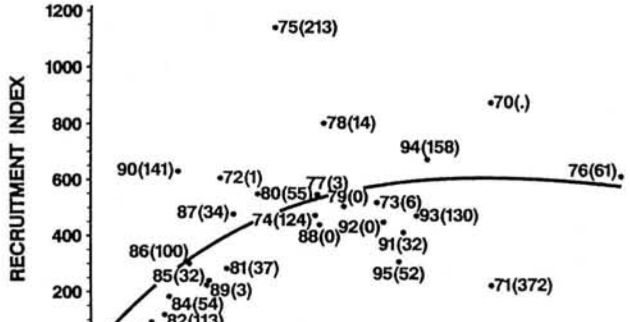

Fig. 3. Relationship between spawning stock and recruitment for tiger prawns (*P. esculentus*) in Exmouth Gulf. Recruitment year is shown, with summer rainfall (mm) in parenthesis.

When the recruitment-to-spawner relationship (RSR) and the SRR are combined (Penn and Caputi 1986), the SRR and RSR intersect (i.e. the spawning stock and recruitment are in equilibrium) at about 40 000 h effective fishing effort. This level of fishing effort has been shown historically to result in the maximum sustainable catch of just over 400 t (Caputi 1992); however, the occurrence of catches below this level in more recent years may be due to targeting of larger prawns for market reasons.

Following the collapse of the tiger prawn stock in 1982, management arrangements were introduced to reduce pre-spawning effort on tiger prawns (Penn *et al.* 1989). The resulting variable closure of the tiger prawn grounds is designed to allow a constant escapement of tiger prawns sufficient to provide an optimal level of spawning stock irrespective of annual recruit strength.

King prawn stock

The king prawn stock is most abundant in the northernmost oceanic sector of the Gulf. Production of this species lagged behind that from the tiger prawn stock in the early 1960s before becoming a regular component of the fishery by 1970 (Fig. 2). The subsequent annual production reflects the overall effort in the fishery, as well as the level of targeting of king prawn areas by the fleet. The level of targeting has generally been a function of the annual abundance of king prawns relative to the tiger prawns that occur in the more protected southern sector of the Gulf. No specific SRR analysis has yet been undertaken on this stock, but the production from the stock since 1982 (Fig. 2) does allow some SRR issues to be examined.

With the decline in tiger prawns (1982), management measures were introduced in 1983 to close the southern half of the Gulf and refocus all of the effort onto the more northern king prawn grounds where spawning by king prawns occurs (Penn 1980). This significant additional effort was permitted on the basis that the stock would be resilient to fishing (Penn 1984). The annual production from this stock (after 1983) now ranges from about 300 t to 500 t (mean 415 t) compared with 200–400 t (mean 291 t) in the previous decade, a 40% increase.

This increased targeted effort on king prawns has clearly resulted in higher catch levels and therefore can be assumed to have decreased the abundance of spawning king prawns over an extended period. Despite these changes there has been no downward trend in king prawn catch and the typical cycle of variation, presumably due to some environmental effects on recruit survival, has continued. With the effective closure of the tiger prawn fishery, levels of effort similar to those that had collapsed the tiger prawn stock were transferred to the king prawn stock; hence, it can be inferred that king prawns are less likely to be susceptible to recruitment overfishing in this fishery at least.

Endeavour prawn stock

The endeavour prawn stock tends to overlap the distribution of the tiger prawns in the southern sector of the Gulf and, to some extent, the king prawns in the north (Penn *et al.* 1989). It is a lower-value species, and effort is generally not targeted towards its capture, thus making the interpretation of the catch and catch-per-unit-effort (CPUE) data more complex. No SRR analysis has been undertaken on this stock; however, production did not decline in parallel with the tiger prawn stock despite the application of similar fishing pressure during the late 1970s and early 1980s. From this catch history it appears that the endeavour prawn stock in Exmouth Gulf is less likely to be affected by fishing than the tiger prawn stock.

SHARK BAY FISHERY

The fishery for prawns in Shark Bay began in 1962, following exploratory fishing in the late 1950s. The major species taken are western king prawns and tiger prawns, with endeavour prawns and a variety of smaller species (coral prawns) taken as a minor bycatch. Since the early 1980s, the dynamics of the fishery have also been affected by the availability of a scallop species (*Amusium balloti*), which is taken as a bycatch. This actively-swimming scallop provides a highly variable trawl catch ranging between 500 t and 20 000 t live weight annually, with a 'typical' year producing approximately 3000 t. The scallops are taken as a bycatch by the dedicated prawn trawl fleet (27 vessels) and as a target catch by a dedicated fleet of 14 full-time scallop trawlers. The availability of scallops can have a highly variable impact on the prawn fishery and cause significant bias in the prawn catch rates in some years. The scallop stock largely overlaps the distribution of the mature spawning segment of the king prawn stock (Penn 1980) and therefore causes the greatest bias in the king prawn catch–effort information. On some occasions (Fig. 4), when the scallops have been very abundant, e.g. 1991–93, their presence has effectively reduced the effort on prawns by reducing the maximum duration of prawn trawl shots from approximately 1.5 h to a few minutes, after which the catches became too heavy to bring onboard.

King prawn stock

Trawling for king prawns began in the southern sheltered waters of the Bay in 1962. By 1970 king prawn catches had increased to approximately 1000 t and all parts of the stock were being exploited. Management of the fishery was based on a limited-entry system (Bowen and Hancock 1984), which allowed controlled expansion of the fleet. Management was, however, fairly conservative, because a severe short-term decline in king prawn catches in the 1966 and 1967 seasons had raised concerns about the sustainability of the stock and/or the habitat. Both catch and fleet size were expanded through to the end of the 1970s, before the decline in the alternative tiger prawn stock caused a reassessment of the optimum fishing effort. Subsequently (1990), an industry-funded buy-back scheme was introduced, which reduced the fleet from 35 to 27.

Assessment of the status of the king prawn stock has traditionally focussed on stock production models (Hall and Penn 1979; Penn *et al.* 1989), to set target levels of effort. More recently, Caputi *et al.* (1997) investigated the relationship between stock and recruitment and found no significant relationship up to present levels of effort. However, a relationship between recruitment and an environmental factor (Caputi *et al.* 1996; Lenanton *et al.* 1991) has been found. This positive correlation ($r = 0.51$) was between recruitment and sea level (sea level reflects the strength of the Leeuwin Current, which brings warm tropical water to the Bay in autumn–winter each year). The hypothesis proposed to explain this effect is that temperature affects catchability (Penn 1984; Joll and Penn 1990) and/or growth of king prawns at recruitment time (April–May). Examination of the effects of spawning stock and environment (sea level) simultaneously (Fig. 5) confirms that spawning stock does not have a significant influence on recruitment.

The king prawn stock appears to be fairly resilient to fishing pressure in Shark Bay; with the decline in the alternative species (tiger prawns) in the 1980s, additional targeting of effort towards king prawns occurred, which appears to have resulted in increased catch levels from the same level of recruits but no longer-term reduction in recruitment. The lower catches since 1989 appear to be the result of lower effort levels resulting from

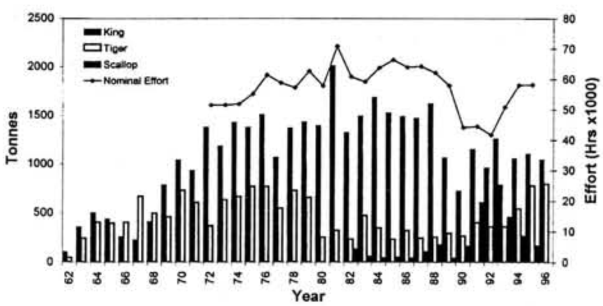

Fig. 4. Catches of the two major prawn species and scallops (meat weight) taken from the Shark Bay fishery (1962–95) and nominal hours of trawling by the prawn fleet.

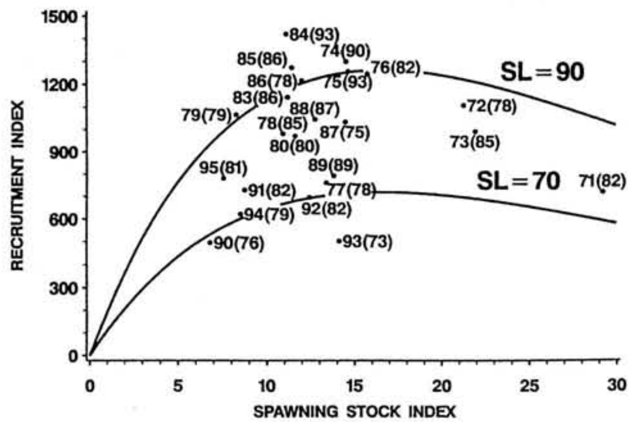

Fig. 5. Relationship between spawning stock, recruitment and sea level (reflecting the influence of the Leeuwin Current) for the king prawn stock in Shark Bay, derived from the indices described in Caputi *et al.* (1997). Recruitment year is shown, with sea level in parenthesis.

the buy-back scheme and an unusually weak Leeuwin Current in the early 1990s due to an extended El Niño Southern Oscillation (ENSO) event (Caputi *et al.* 1996), and a corresponding increase in abundance of scallops. This unusually high biomass of scallops both biased the king prawn CPUE data, on which the recruitment index is based, and reduced the effort on king prawns, thus resulting in lower catch. The interactions of these factors are still being evaluated, but the return of catches to expected levels of 1000 to 1200 t with the end of the 3–4-year ENSO event, and higher effort levels, suggest that catch downturn was driven by the environment rather than by spawning stock abundance.

Tiger prawn stock

Fishing for tiger prawns developed as an activity secondary to fishing for king prawns but became a major part of the catch in the mid 1960s. During the 1970s, tiger prawn catches increased to an average of about 650 t per year (Fig. 4) and tended to have a reciprocal relationship with king prawn catches each year owing to targeting by the vessels. Following an increase in effective effort on tiger prawns in the late 1970s, resulting from vessel replacements and improved targeting on localized areas of high tiger prawn abundance using radar technology, the catch declined to an average of 300 t during the 1980s (Fig. 4). Assessment of this decline indicated that recruitment of tiger prawns was strongly correlated with spawning stock levels, and that fishing effort had been responsible for reduced spawning stock levels (Penn *et al.* 1989). No significant environmental effect on recruitment to explain this decline could be identified.

Examination of the SRR (Fig. 6) updated from Penn *et al.* (1995) indicates that the original assessment that recruitment declined as a result of reduced breeding stock levels continues to be supported (r = 0.64) by the data from additional years (Caputi *et al.* 1997). Because tiger prawns form only a minor proportion of the catch from Shark Bay, management action to improve levels of tiger prawn breeding stocks was not introduced until the late 1980s. This lack of management action when compared with the situation in Exmouth Gulf has

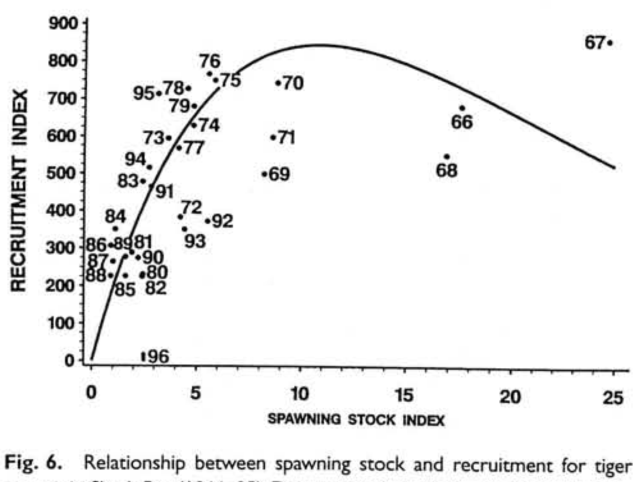

Fig. 6. Relationship between spawning stock and recruitment for tiger prawns in Shark Bay (1966–95). Data points show the year of recruitment.

enabled the two fisheries to be treated as a fortuitous case of experimental management, with the Shark Bay stock being a 'control' for Exmouth Gulf for a period of ten years (Penn *et al.* 1995). A further implication flowing from the Shark Bay assessment is that the tiger prawn stock in this fishery appears to have reached a recruitment equilibrium at about 300 t production, equivalent to a recruitment index of 250–350 in the 1980s (Fig. 6). The increase in tiger prawn recruitment since 1991 appears to be due to an increase in spawning stock (Caputi *et al.* 1997), as a result of an overall reduction in effort due to a buy-back scheme and because most prawn trawlers focussed on scallop and king prawn areas, away from tiger prawn areas.

Control of exploitation in the Shark Bay prawn fishery is achieved by a system of both temporal and spatial closures primarily aimed at optimizing the yield of the more abundant king prawns. Owing to the largely overlapping distribution of the king and tiger prawns, specific management to protect breeding stocks of the more susceptible tiger prawns has been restricted to overall controls on effort through the seasonal closure system (Penn *et al.* 1989), and to a general buy-back scheme in 1990. This buy-back scheme was designed to provide effort levels corresponding to equilibrium catches of about 1100 t of king prawns and 500 to 600 t of tiger prawns, while maintaining tiger prawn spawner indices of approximately 5 kg h^{-1}. In 1996, however, a new specific closure to protect tiger prawn spawning areas before and during the August to October spawning season (Penn *et al.* 1995) has been proposed. This system is being modelled on the Exmouth Gulf pre-spawning closure system, which is designed to leave an optimal (safe) level of spawning stock each year.

Review of penaeid recruitment overfishing

In reviewing data from a number of penaeid fisheries prior to 1981, Penn (1984) hypothesized that more-catchable species should be first to show evidence of recruitment overfishing. Using data from observations in aquaria, Penn (1984) categorized penaeid species into three broad behavioural–catchability types, of which the more catchable type-2 and type-3 schooling species were expected to be most susceptible to fishing. Subsequent field experiments (Penn, unpublished) using the methods of Joll and Penn (1990) have confirmed the differences in catchability in the field between the type-1 (lowest catchability) and type-2 (medium catchability) species which provide the majority of the Western Australian case studies. In reviewing the hypothesis of Penn (1984) and the subsequent fate of the various species in the Western Australian fisheries it is apparent that these particular stocks generally fit the 1984 hypothesis. However, a number of other stocks (Table 1) now considered to have suffered from recruitment overfishing are not all type-2 or type-3 species. Conversely, a number of type-3 stocks identified as being at high risk by Penn (1984), e.g. *P. merguiensis* (Gulf of Carpentaria, Staples *et al.* 1995) and *P. setiferus* (Gulf of Mexico, Nance 1995), have continued without significant change since 1981. Similarly, the heavily fished type-2 stock of *P. aztecus* in the Gulf of Mexico (Nance 1995) has shown a slight increasing trend in recruitment since the 1960s.

Table 1. Penaeid prawn stocks considered to have suffered from recruitment overfishing, their behaviour catchability type (after Penn 1984), and reference

Type 1(low)	*P. latisulcatus* (South Australia)	Gulf St Vincent	Morgan (1995)
	P. latisulcatus (South Australia)	Venus Bay	Anon. (1978)
Type 2(medium)	*P. esculentus*	Exmouth Gulf (Western Australia)	Penn *et al.* (1995)
	P. esculentus	Shark Bay (Western Australia)	Penn *et al.* (1995)
	P. esculentus[A]	Gulf of Carpentaria (Northern Australia)	Somers (1994)
	P. semisulcatus	Saudi Arabia (Arabian Gulf)	Morgan and Garcia (1982)
Type 3(high)	*P. merguiensis*	Exmouth Gulf (Western Australia)	Penn *et al.* (1989) this paper
	P. setiferus	Western Gulf of Mexico (Mexico)	Gracia (1996)

[A]Recruitment overfishing has not been formally reported for this stock; however, a significant reduction in pre-spawning fishing effort has been legislated, and catches have returned to about half of the historical peak production level.

DISCUSSION

Subsequent to the reviews of the possibilities for recruitment overfishing in penaeid fisheries (Garcia 1983; Penn 1984), two clearly documented cases of recruitment overfishing have now been reported for *P. esculentus* stocks in WA (Penn and Caputi 1986; Penn *et al.* 1995). Data on *P. esculentus* in the Gulf of Carpentaria (Somers 1994) also suggest that recruitment overfishing may have contributed to a significant reduction in catch from that fishery. Recruitment overfishing is also apparent in two of the three stocks of *P. latisulcatus* in South Australia (J. Keesing, pers. comm.; Morgan 1995) and has occurred with *P. setiferus* in Mexico (Gracia 1991). The historically depleted stock of *P. merguiensis* in Exmouth Gulf (Penn 1984) has also failed to recover over a 25-year period. Similarly the previously significant fishery for schooling *P. semisulcatus* in Arabian Gulf waters has apparently not recovered to its levels of the 1950s and 1960s, although some sectors have staged short-lived recoveries, e.g. off Saudi Arabia (Morgan and Garcia 1982), following significant reductions in fishing activity.

Although the number of stock failures in which recruitment overfishing has been implicated have increased during the 1980s, the majority of penaeid stocks still continue to show considerable resistance to fishing pressure. In most of these resilient penaeid stocks, variation in recruitment is more often related to environmental influences on recruitment (Staples *et al.* 1995) rather than to breeding stock abundance, although these data are rarely available. Such correlations between recruitment and environmental factors have mostly been shown in temperate and subtropical stocks where such environmental variation is probably greater. Conversely, recruitment variability should be less in tropical fisheries where most penaeid stocks live; however, recruitment in these areas has received little research attention to date (Staples *et al.* 1995).

There are also many penaeid fisheries where significant multi-year cycles in catches occur and an environmental influence on recruitment is assumed but cannot be identified. In these situations there is a possibility, yet to be evaluated, that heavy but intermittent fishing pressure on spawning stocks could generate such cycles in recruitment. For example the SRR/RSR model developed for the Exmouth Gulf tiger prawn stock (Penn and Caputi 1986) suggests that if fishing severely depletes a stock and the fleet moves away when recruitment fails, the stock would recover fully in two seasons from an almost total collapse. That is, with a relatively mobile fleet focussing heavy fishing pressure on a series of stocks, there is the potential to generate three- or four-year cycles in recruit abundance, which would give the appearance of being environmentally driven.

Penn (1984) hypothesized that more-catchable species would be the first to show the effects of fishing on spawning stocks and exhibit recruitment overfishing. The present review indicates that there are now examples from all three catchability types in which recruitment overfishing has been implicated. Further examination of the three depleted Western Australian stocks (Penn and Caputi 1985, 1986; Penn *et al.* 1995) indicates a number of factors in addition to catchability that appear to have contributed to the decline in spawning stocks and recruitment. Firstly, both *P. esculentus* stocks aggregate or concentrate at time of spawning, owing to their geographic situation in embayments and their preference for discrete and spatially restricted habitats. Secondly, both stocks are exploited in multi-species situations, where there is sufficient overlap to allow the alternative species (*P. latisulcatus*) to effectively subsidize the cost of fishing. This has allowed fishing to continue to reduce spawner biomass to levels normally uneconomic to trawl. Another factor common to these stocks has been the more restricted spawning season for the tiger prawns near the southern limit of their range (lat. 22–26°S); this has allowed a high level of pre-spawning effort. In both tiger prawn stocks, the reduction in spawning biomass has been to approximately 20% of virgin levels before recruitment reductions became evident in the catch. In contrast, the alternative low-catchability type-1 species in these fisheries, *P. latisulcatus*, does not aggregate at spawning, is not habitat specific, and is in the middle of its geographic range (Penn 1980); in these stocks, spawning is protracted and a low proportion of the fishing effort is pre-spawning.

Examination of the other cases of possible recruitment overfishing suggests that the position of stock within the species geographic range could be a common factor. For example, the two *P. latisulcatus* stocks in South Australia are at the extreme end of the range of the species (lat. 35°S) where they can be expected (Penn 1980) to have a particularly short spawning season and do not start spawning until their second year of life (Morgan 1995). In South Australia the majority of fishing effort and hence mortality can therefore occur prior to spawning. Both Gulf St Vincent and Venus Bay stocks also occur in embayments, which are likely to cause stock aggregation at spawning time. The *P. semisulcatus* stocks in the Arabian Gulf are in a similar situation, being at the northern limit of their range (30°N), and they sometimes exhibit schooling (aggregation behaviour) at high stock sizes (Morgan and Garcia 1982; Penn 1984), thereby

Table 2. Frequency of some risk factors contributing to identified cases of recruitment overfishing. Abbreviations in parentheses refer to localities identified in Table 1

		Risk Factors			
		Embayment Location	Range Position	Catchability Type	Multi/Single Species
P. latisulcatus	(GSV)	Yes	Edge	Low	Single
P. latisulcatus	(VB)	Yes	Edge	Low	Single
P. esculentus	(EG)	Yes	Edge	Medium	Multi
P. esculentus	(SB)	Yes	Edge	Medium	Multi
P. esculentus	(GOC)	No	Middle	Medium	Multi
P. semisulcatus	(AG)	No	Edge	Medium	Multi
P. merguiensis	(EG)	Yes	Edge	High	Multi
P. setiferus	(Mex)	No	Middle	High	Single

increasing the potential impact of fishing. Similarly, *P. merguiensis* in Exmouth Gulf (Penn and Caputi 1986) is a (highly aggregating) schooling species at the southern limit of its range (lat. 22°S), where historic fishing would have occurred mostly in the pre-spawning period.

In contrast, the tiger prawn stock (*P. esculentus*) in the Gulf of Carpentaria, which has shown signs of recruitment depression (Somers 1994) is closer to the centre of its geographic range, and is not confined in an embayment. However, in one of the major fishing areas in the northwestern Gulf the stock does tend to be concentrated in relatively discrete areas, owing to the presence of islands where a large highly sophisticated fleet congregates each year.

In summary, this review of instances of recruitment overfishing identified during the past decade suggests that a combination of factors has usually contributed to the cases in which a reduction of spawning stock appears to have led to recruitment failure. These examples suggest that the stocks at higher risk are those where the circumstances of the stock and associated fishery enable the generation of significant pre-spawning fishing mortality. This is often most likely in situations where the species is at the edge of its geographic range so that spawning season and hence egg production is more limited (Penn 1980). These fisheries also tend to be in localities where direct environmental effects on recruit variability are likely to be greatest, and where low stock sizes can also occur by chance because of environmental effects but are then maintained low if heavy fishing effort continues. Similarly, a variety of factors, e.g. behaviour (after Penn 1984) and habitat preference, can contribute to the increased catchability and exploitation of a stock. Equally, the situation of minor species in a multiple-stock fishery can contribute to unusually high levels of fishing mortality. The frequency of occurrence of these factors for the eight stocks identified in Table 1 shows that embayment and geographic range factors occur in five and six cases, that behaviour type is spread across all three types, and that multi-species fisheries occur in five instances (Table 2).

Identification of high-risk penaeid stocks using this array of factors is suggested as a measure of directing research towards fisheries where it is most likely to provide relevant information to support management needs. In these fisheries where the stocks are at higher risk, there also needs to be an increased focus on the development and maintenance of long-term fishery databases designed to enable both the effects of fishing effort on spawning stocks and the effects of environment and spawning stock on recruitment to be determined (Caputi 1992). Penaeid stocks assessed to be in the high-risk category should also be subject to more conservative management under the precautionary principle advocated by Garcia (1996). Given that the increasing use of electronic technology by fishermen to identify areas of localized stock abundance has the potential to significantly increase exploitation rates in all penaeid fisheries, monitoring of spawning stock levels should be given increased research priority in future.

References

Anon. (1978). Prawn tagging results in the Gulf of St Vincent and Investigator Strait. *South Australian Fishing Industry Council* **2**(2), 10–12.

Anon. (1996). State of the Fisheries 1994–95. (Fisheries Department Western Australia). 134 pp.

Bowen, B K, and Hancock, D A (1984). The limited entry prawn fisheries of Western Australia: research and management. In 'Penaeid Shrimps, their Biology and Management'. (Eds J A Gulland and B J Rothschild) pp. 272–89 (Fishing News Books: Surrey, England).

Caputi, N (1992). Spawning stock–recruitment relationships. In 'Recruitment Processes, Australian Society for Fish Biology Workshop (held in Hobart, August 1991)'. (Ed D A Hancock) pp. 142–9.

Caputi, N W, Fletcher, R, Pearce, A, and Chubb, C (1996). Effect of the Leeuwin current on the recruitment of fish and invertebrates along the Western Australian coast. *Marine and Freshwater Research* **47**, 147–55.

Caputi, N, Penn, J W, Joll, L M, and Chubb, C F (1997). Stock-recruitment–environment relationships for invertebrate species of Western Australia. *Canadian Fisheries and Aquatic Sciences Special Publication* 125.

Garcia, S (1983). The stock–recruitment relationship in shrimps: reality or artefacts and misinterpretations? *Oceanographie Tropicale* **18**, 25–48.

Garcia, S M (1996). Stock–recruitment relationships and the precautionary approach to management of tropical shrimp fisheries. *Marine and Freshwater Research* **47**, 59–65.

Gracia, A (1991). Spawning stock–recruitment relationships of white shrimp in the southwestern Gulf of Mexico. *Transactions of the American Fisheries Society* **120**, 519–27.

Gracia, A (1996). White shrimp (*Penaeus setiferus*) recruitment overfishing. *Marine and Freshwater Research* **47**, 59–65.

Gulland, J A (1984). Introductory guidelines to shrimp management: some further thoughts. In 'Penaeid Shrimps, their Biology and Management'. (Eds J A Gulland and B J Rothschild) pp. 290–9 (Fishing News Books: Surrey, England).

Hall, N G, and Penn, J W (1979). Preliminary assessment of effective effort in a two species trawl fishery for penaeid prawns in Shark Bay, Western Australia. *Rapports et Procès-verbaux des Réunions, Conseil international pour l'Exploration de la Mer* **175**, 147–54.

Joll, L M, and Penn, J W (1990). The application of high resolution navigation systems to Leslie–Delury depletion experiments for the measurement of trawl efficiency under open sea conditions. *Fisheries Research* **9**, 41–55.

Lenanton, R C, Joll, L M, Penn, J W, and Jones, K (1991). The influence of the Leeuwin Current on coastal fisheries in Western Australia. In 'The Leeuwin Current: an Influence on the Coastal Climate and Marine Life of Western Australia'. (Eds A F Pearce and D I Walker). *Journal of the Royal Society of Western Australia* **74**, 101–14.

Morgan, G R (1995). Assessment, management and research support for the Gulf St Vincent prawn fishery. *South Australian Fisheries Management Series* **12**. 35 pp.

Morgan, G R, and Garcia, S (1982). The relationship between stock and recruitment in the shrimp stocks of Kuwait and Saudi Arabia. *Oceanographie Tropicale* **17**(2), 133–7.

Nance, J M (1995). Stock assessment report 1994 Gulf of Mexico shrimp fishery. (NMFS. SEFSC Galveston Laboratory: United States). 15 pp.

Penn, J W (1980). Spawning and fecundity of the western king prawn, *Penaeus latisulcatus* Kishinouye, in Western Australian waters. *Australian Journal Marine and Freshwater Research* **31**, 21–35.

Penn, J W (1984). The behaviour and catchability of some commercially exploited penaeids and their relationship to stock and recruitment. In 'Penaeid Shrimps, their Biology and Management'. (Eds J A Gulland and B J Rothschild) pp. 115–40 (Fishing News Books: Surrey, England).

Penn, J W and Caputi, N (1985). Stock recruitment relationships for the tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia and their implications for management. In 'Second Australian National Prawn Seminar'. (Eds P C Rothlisberg, B J Hill and D J Staples) pp. 165–73 (Cleveland: Australia).

Penn, J W, and Caputi, N (1986). Spawning stock–recruitment relationships and environmental influences on the tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia. *Australian Journal of Marine and Freshwater Research* **37**, 491–505.

Penn, J W, Hall, N G, and Caputi, N (1989). Resource assessment and management perspectives of the penaeid prawn fisheries of Western Australia. In 'Marine Invertebrate Fisheries: their Assessment and Management'. (Ed J F Caddy) pp. 115–40.

Penn, J W, Caputi, N, and Hall, N G (1995). Spawner–recruit relationships for the tiger prawn (*Penaeus esculentus*) stocks in Western Australia. *ICES Marine Science Symposia (Actes du symposium)* **199**, 320–33.

Somers, I F (1994). Species composition and distribution of commercial penaeid prawn catches in the Gulf of Carpentaria, Australia, in relation to depth and sediment type. *Australian Journal of Marine and Freshwater Research* **45**, 317–36.

Staples, D J, Vance D J, and Loneragan, N R (1995). Penaeid prawn recruitment variability: effect of the environment. In 'Proceedings of the Workshop on Spawning Stock–Recruitment Relationships (SRRs) in Australian Crustacean Fisheries'. (Eds A J Courtney and M G Cosgrove) pp. 41–8 (Department of Primary Industries: Queensland).